A STUDY OF COMPACT OBJECT MERGERS AS SHORT GAMMA-RAY BURST PROGENITORS

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Draft version February 5, 2008

ABSTRACT

We present a theoretical study of double compact objects as potential short/hard gamma-ray burst (GRB) progenitors. An updated population synthesis code `StarTrack` is used to calculate properties of double neutron stars and black-hole neutron star binaries. We obtain their formation rates, estimate merger times and finally predict their most likely merger locations and afterglow properties for different types of host galaxies. Our results serve for a direct comparison with the recent *HETE-II* and *SWIFT* observations of several short bursts, for which afterglows and host galaxies were detected. We also discuss the possible constraints these observations put on the evolutionary models of double compact object formation. We emphasize that our double compact object models can successfully reproduce at the same time short GRBs within both young, star-forming galaxies (e.g., GRB 050709 and GRB 051221A), as well as within old, elliptical hosts (e.g., GRB 050724 and probably GRB 050509B).

Subject headings: gamma ray bursts: progenitors — binaries: close — stars: evolution, formation, neutron — black hole physics

1. INTRODUCTION

The recent detections of afterglows for short/hard GRBs have made possible a breakthrough in the study of this class of bursts. *Swift* (Gehrels et al. 2005; Barthelmy et al. 2005) and *HETE-II* (Villasenor et al. 2005) observations led to precise localizations of several short GRBs, and subsequent follow-up optical observations allowed for tentative connections with their host galaxies and a measurement of their redshifts. GRB 050509B was found to lie in the vicinity of a large elliptical galaxy, with no current star formation and at a redshift of 0.225 (Gehrels et al. 2005). GRB 050709 was found in the outskirts of a dwarf irregular galaxy with ongoing star formation at redshift 0.1606 (Hjorth et al. 2005; Fox et al. 2005; Covino et al. 2006), as was GRB 051221A (Soderberg and Berger 2005, Berger and Soderberg 2005) at redshift 0.5465. GRB 050724 was found within a small elliptical galaxy with no current star formation at a redshift of 0.258 (Berger et al. 2005a). GRB 050813 was found close to a cluster of galaxies at redshift 1.7-1.9 (Berger 2005b), but no host galaxy has been proposed.

Compact object mergers from double neutron star (NS-NS) and black hole neutron star (BH-NS) binaries have been proposed for the first time by Paczynski (1986) and then further discussed as the central engines of short GRBs by number of authors (e.g., Eichler et al. 1989; Narayan, Paczynski & Piran 1992). Observational constraints on these populations may be obtained only for NS-NS systems since only such binaries are currently observed as binary pulsars. Merger rates derived from the observed

sample of a handful of Galactic relativistic NS-NS binaries have been presented by Kalogera et al. (2004 and references therein). Double compact objects with both neutron stars and black holes can be studied via population synthesis methods (e.g., Lipunov, Postnov & Prokhorov 1997; Portegies Zwart & Yungelson 1998; Belczynski, Kalogera & Bulik 2002c) There were several early population synthesis studies in the context of potential GRB progenitors (e.g., Bloom, Sigurdsson & Pols 1999; Belczynski & Bulik 1999; Fryer, Woosley & Hartmann 1999). In particular, it was found that NS-NS and BH-NS mergers are expected to take place outside host galaxies with long delay times. However, it has only recently been recognized that the population of the double compact objects may be more diverse than was previously believed (Belczynski & Kalogera 2001; Belczynski, Bulik & Rudak 2002b; Perna & Belczynski 2002; Belczynski, Bulik & Kalogera 2002a). In addition to classical well-recognized channels, these newly recognized formation channels lead to the formation of tighter double compact objects, with short lifetimes and therefore possible prompt mergers within hosts. The new formation scenarios were independently confirmed by detailed evolutionary calculations (Ivanova et al. 2003; Dewi & Pols 2003).

In this study we perform an updated analysis of double compact object mergers using population synthesis methods. Over the last several years and since our previous studies, the `StarTrack` population synthesis code has undergone major revisions and updates, many of which are guided and tested through comparisons with either obser-

vations or detailed evolutionary calculations (see Belczynski et al. 2005). Additionally, this new study is motivated by the recent short GRB observations and their likely connection with double compact object mergers. In §2 we present the overview of our claculations. In §3 the double compact object formation, merger rates, locations and their afterglow properties are presented. Finally, in §4 we discuss our results in context of the recent short-GRB observations.

2. BINARY COMPACT OBJECT MODELS

Binary Population Synthesis. The `StarTrack` population synthesis code was initially developed for the study of double compact object mergers in the context of GRB progenitors (Belczynski et al. 2002b) and gravitational-wave inspiral sources (Belczynski et al. 2002c). In recent years `StarTrack` has undergone major updates and revisions in the physical treatment of various binary evolution phases. The new version has already been tested against observations and detailed evolutionary calculations (Belczynski et al. 2005), and has been used in various applications (e.g., Belczynski & Taam 2004; Belczynski et al. 2004a; Belczynski, Sadowski & Rasio 2004b). The most important updates for compact object formation and evolution include: a full numerical approach to binary evolution due to tidal interactions and coupling calibrated using high mass X-ray binaries and open cluster observations, a detailed treatment of mass transfer episodes fully calibrated against detailed calculations with a stellar evolution code, updated stellar winds for massive stars, and the latest determination of natal kick velocity distribution for neutron stars (Hobbs et al. 2005). In the helium star evolution, which is of a crucial importance for the formation of new classes of double compact objects (e.g., Ivanova et al. 2003), we have applied a conservative treatment matching closely the results of detailed evolutionary calculations. The NS-NS progenitors are followed and checked for any potential Roche lobe overflow (RLOF). While in the mass transfer phase, systems are examined for potential development of dynamical instability, in which case the systems are evolved through a common envelope phase. We treat common envelope events through the energy formalism (Webbink 1984; Belczynski et al. 2002), where the binding energy of the envelope is determined from the set of He star models calculated with the detailed evolutionary code by Ivanova et al. (2003). For some systems we observe, as before, extra orbital decay leading to the formation of very tight short lived double compact object binaries. However, since the progenitor evolution and the final RLOF episodes are now followed in much greater detail, we note significant differences from our earlier studies. For a detailed description of the revised code we refer the reader to Belczynski et al. (2005).

Galaxy Potential Models. To investigate the motion of binary compact objects in their host galaxies and study the merger locations we consider a set of typical gravitational potential models for different types of galaxies. Our model spiral galaxy is identical to the one used in Belczynski et al. (2002b). It consists of a disk, bulge, described by a Miyamaoto & Nagai (1975) type potential and a halo with the dark matter density of $\rho = \rho_c[1 + r/r_c{}^2]^{-1}$. We consider: a large spiral similar to the Milky Way, with

a disk and bulge mass of 10^{11} M$_\odot$ and a massive halo of 10^{12} M$_\odot$ extending out to 100kpc; and a small spiral downscaled by a factor of 10^3 in mass and of 10 in size (constant density). We place the binaries on circular orbits in the disk of a spiral galaxy. Binaries with the full range of delay times (i.e., time from the formation of a double compact object binary until the merger) are used here since spirals consists of both old and young populations due to a roughly continuous star formation history. We also consider elliptical host galaxies. The model potential of an elliptical galaxy consists of two components: the bulge and the halo. The bulge is described by the Hernquist (1990) potential: $\Phi(r) = -GM_e(r + a_e)^{-1}$, where M_e the mass of the bulge and a_e is a measure of its size. For the halo we use the same model as in the case of spiral galaxies described above. The Hernquist potential has a simple analytical form and it reproduces the brightness profile observed typically in ellipticals. We consider two extreme cases: a large elliptical with $M_e = 5 \times 10^{11} M_\odot$, and $a_e = 5$ kpc, and a small elliptical with mass 10^3 times smaller and size 10 times smaller. The mass and dimension of the halo are scaled identically as the bulge. The binaries are placed on circular orbits with a random angular momentum direction in the bulge with a mass density corresponding to the Hernquist potential $\rho(r) = (M_e/2\pi)a_e r^{-1}(a_e + r)^{-3}$. Only binaries with delay times greater than 1 Gyr are considered for ellipticals, since these galaxies contain only old populations. For starburst galaxies we use the same potential model as for spirals, although starbursts are mostly irregular. We consider a large and a small starburst modeled by the large and small spiral galaxies. Only binaries with delay times shorter than 1 Gyr are considered since starbursts are young, star-forming galaxies.

Afterglow Calculations. We use the mass density profiles corresponding to the galactic potentials for the model galaxies described above to predict the luminosity distribution of the afterglows. The baryonic fraction is assumed to be 20% for the disk, and 0.04% for the bulge and halo (e.g. Fukugita, Hogan & Peebles 1998). We compute the expected luminosities of the afterglows in the [2-10] keV energy band using the standard synchrotron model (Sari, Piran & Narayan 1998). The bursts energy is assumed to be $E = 5 \times 10^{49}$ erg, given the observed values of $E_\gamma \sim 5 \times 10^{48}$ erg or less (e.g. Fox et al. 2005), and for a typical efficiency of conversion of total energy into γ-rays $\eta_\gamma \sim 0.1$. Other afterglow parameters are drawn from random distributions within their typical ranges (see Perna & Belczynski 2002 for details).

3. RESULTS

In what follows we present and discuss our results obtained from our reference population synthesis model, as described in great detail in Belczynski et al. 2005. Assumptions regarding primordial binary characteristics and binary evolution treatment are typical of what is widely used in the literature. Variations of these assumptions (for these too see Belczynski et al. 2005) do of course lead to quantitative differences in the results; however our goal in this study is to concentrate on the robust characteristics of double compact objects in the context of the recent short GRB observations.

Double Compact Object Formation. Double compact objects form from massive progenitor systems. The more massive primary star evolves off the main sequence and eventually fills its Roche lobe initiating the first mass transfer (MT) episode. The MT is dynamically stable (due to binary components of comparable mass), and leads to moderate orbital tightening. The primary loses its envelope and forms a Helium star, which soon afterwords explodes in a Type Ib supernova (SN) forming the first compact object. Later on, the secondary evolves off the main sequence, and fills its Roche lobe while on the red giant branch, initiating a second MT episode. Most commonly, due to the extreme mass ratio (first compact object: $\sim 1 - 2$ M$_\odot$ for neutron stars, secondary $\sim 8 - 15$ M$_\odot$) the MT is dynamically unstable and the system enters a common envelope phase. The envelope of the secondary is ejected at the cost of orbital energy, and the system separation is typically reduced by $\sim 1 - 2$ orders of magnitude. The system emerges as a close binary consisting of the first compact object and a naked helium star (the core of the original secondary). At this point the evolution may follow two qualitatively different paths.

Classical formation channel: The helium star evolves and never fills its Roche lobe. The evolution stops at the point where the helium star explodes in a Type Ib SN forming the second compact object. Provided that the SN explosion does not disrupt the binary, a double compact object is formed on a rather wide orbit (e.g., Bhattacharya & van den Heuvel 1991).

New formation channel: If the helium star has low mass ($\lesssim 3 - 4$ M$_\odot$), it is known to expand at the later stages of its evolution (e.g., see Belczynski & Kalogera 2001 for a discussion and references). Since the binary is rather tight (after the common envelope phase) the Helium star at some point overfills its Roche lobe and initiates a third MT episode. For many cases this MT is dynamically stable (Ivanova et al. 2003; Dewi & Pols 2003) and the orbital separation decreases further, until the helium star explodes in a Type Ib/c SN forming the second compact object. A double compact object is then formed with a very tight (ultracompact) orbit (e.g., Belczynski & Kalogera 2001; Belczynski et al. 2002a,c; Ivanova et al. 2003).

Merger Times. There are two characteristic times related to the formation and the subsequent evolution of double compact object binaries. First, there is an evolutionary time: the time required for the initial progenitor binary (two components on Zero Age Main Sequence) to form a binary with two compact objects. Second, there is a merger time, which is set by the orbital decay of a double compact object binary due to the emission of gravitational radiation. The delay time (sum of the evolutionary time and merger time) as well as merger time distributions for NS-NS and BH-NS binaries are shown in Figure 1.

It can be seen that merger time distributions are bimodal. The very tight binaries ($t_{\rm mer} \sim 0.001 - 0.1$ Myr) originate from the new formation channel described above. They involve progenitors which experience an extra MT episode, that leads to additional orbital decay and thus the formation of systems with very tight orbits. Long-lived binaries (with $t_{\rm mer} \sim 100$ Myr – 15 Gyr) are formed through classical channels. On the other hand, delay time distributions in a range of 10 Myr – 15 Gyr are rather flat, with prominent peaks at $t_{\rm del} \sim 20$ Myr. Evolutionary times of double compact objects are of the order of 10–20 Myr, therefore the systems with very short merger times are shifted in the delay time distribution toward higher values, and in particular they form the peak around 20 Myr. The flat plateau is created by long-lived binaries. In the model presented here (our "standard" model), we have adopted a maximum NS mass of 2 M$_\odot$. Compared to our standard model, for a maximum NS mass of 3 M$_\odot$, approximately 90% of the BH-NS become NS-NS and the remaining BH-NS binaries (10%) are wide binaries formed through the classical channels. The highest NS mass estimate is 2.1 ± 0.2 M$_\odot$ for a millisecond pulsar in PSR J0751+1807; a relativistic binary with helium white dwarf secondary (Nice et. al. 2005).

Merger Rates. Throughout the paper, we adopt a flat cosmology ($\Omega_{\rm m} = 0.3$, $\Omega_\Lambda = 0.7$ and $H_0 = 70$ km s^{-1} Mpc^{-1}, and use the star-formation history (corrected for extinction) presented by Strolger et al. (2004). We should however point out that, in general, the star formation rate is expected to be rather different in ellipticals and in spirals, since most ellipticals were assembled before $z \sim 2$ and they are no longer forming stars, while spirals and starbursts galaxies have an on-going and active star formation (see Smith et al. 2005 for a discussion). We defer this whole issue of the study of the relative contribution of the two types of galaxies to another paper (O'Shaughnessy et al. in preparation).

The merger rates of NS-NS and BH-NS binaries as a function of redshift are shown in Figure 2. We obtain delay times (time to formation of double compact object plus merger time) and mass formation efficiency from population synthesis (for details see Belczynski et al. 2002b). The predicted merger rates as a function of redshift are a convolution of the adopted star formation rate history and the delay times characteristic for NS-NS and BH-NS mergers: The longer the delay times, the greater is the shift of merger events to lower redshifts. With the model distributions of delay times, the peak of NS-NS mergers appears at redshift ~ 1 instead of ~ 3 of the star formation curve (Figure 2). The absolute normalization of the merger rates in Figure 2 is arbitrary, since its value is subject to large uncertainties (1–2 orders of magnitude) due to the some poorly constrained population synthesis model parameters (e.g., Belczynski et al. 2002c).

Merger Locations. We present the distributions of merger locations for different host galaxies in Figure 3. In starburst galaxies, the double compact object population is dominated by new systems with short-merger times, and therefore most of the mergers are expected to be found within hosts (more so for massive galaxies). A small fraction (10-30%, depending on host mass) of mergers takes place outside hosts and these are mergers of classical systems with merger times $\sim 10 - 1000$ Myrs, which are allowed in the model populations due to our rather long adopted age of starburst (1 Gyr). In elliptical galaxies, a substantial fraction of mergers takes place outside hosts at present. In particular, $\sim 80\%$ and $\sim 30\%$ of NS-NS and BH-NS mergers may take place outside of small and large host, respectively. However, we note that even for small hosts we find a small but significant fraction (~ 20-30%) of mergers within several kpc from the host center.

Spiral galaxies hosting both young and old stellar populations represent the intermediate case between starburst and ellipticals.

Afterglows. Figure 4 shows the distribution of the ISM number density in the merger sites, and the corresponding afterglow luminosity in the [2-10] keV band, for the cases of a starburst and an elliptical of small and large dimension and mass. In ellipticals, especially small ones, most mergers occur at rather low densities, therefore resulting in generally dimmer afterglows, a fraction of which could remain undetectable. Such a case of a "naked" burst might be GRB 050911 (Page et al. 2005). For massive ellipticals the majority of mergers take place inside hosts and produces generally detectable afterglows. In large starbursts, mergers take place within the hosts and give rise to rather bright afterglows (due to high typical ISM densities). In small starbursts, the dominant short-lived double compact object population merges within hosts and produces detectable afterglows. However, due to our rather high adopted age of the starburst (1 Gyr) some systems have longer delay times and some can escape from their hosts, producing very dim afterglows. These dim afterglows are not expected for very young starbursts (10–100 Myr).

4. DISCUSSION

We find two distinct populations of binary compact objects in terms of their binary-orbit characteristics and associated merger times due to differences in their evolutionary history. One is a classical population of rather wide, long-lived systems, with merger times of $\sim 100 - 15,000\,\mathrm{Myr}$, and the other consists of tight, short-lived systems with merger times of $\sim 0.001 - 0.2\,\mathrm{Myr}$. In a typical binary evolution model, there are roughly similar numbers of short- and long-lived NS-NS systems, while there are $\sim 20\%$ and $\sim 80\%$ of short- and long-lived BH-NS systems, respectively. The four known Galactic double neutron stars belong to the long-lived classical systems (see Fig. 1), and, given the small number of NS-NS systems, we do not expect to see the short-lived systems, since they merge very soon after their formation.

We find that most of the double compact binaries ($\gtrsim 80\%$) that are formed in *large* galaxies merge within them, independent of the galaxy type. For *small* galaxies, we find that $\sim 20\%$, 50%, 70% mergers take place within elliptical, spiral and starburst hosts respectively (see Fig. 3). The combination of binary compact object lifetimes and their merger locations leads to a testable prediction for the location of mergers in relation to the host galaxies. For starburst galaxies (which on average have small masses) where stellar populations are young, we expect mergers from short-lived double compact objects. These are expected to take place inside or in the vicinity of their hosts. It is worth noting that such locations, and more importantly, the mere existence of double compact object mergers associated with star-forming, young galaxies, is not predicted by any of the previous studies that considered only classical formation scenarios (long-delayed mergers). If it is shown that the star-forming host galaxy of GRB 050709 does not contain a dominant old underlying stellar population, this association will stand as the "smoking gun" evidence for the new short-lived dou-

ble compact object formation channel, originally identified by Belczynski & Kalogera (2001) and Belczynski et al. (2002a,c).

In elliptical galaxies, which have little or no ongoing star formation, we expect to find mergers of long-lived double compact objects at present. For massive hosts, most mergers should occur within the hosts, while for smaller galaxies outside the hosts. GRB 050509B was tentatively associated with a large elliptical galaxy, and its error circle indicates that this burst took place either within or in the outskirts of the host, in agreement with our findings. GRB 050911 appears to be a case of a "naked" burst (Page et al. 2005). It could possibly be explained by our models with a double compact object binary originating from a small elliptical galaxy and merging far outside the host without any detectable afterglow. On the other hand GRB 050724 was found inside a small elliptical. Our models are consistent with this observation, since $\sim 20\%$ of mergers are predicted to occur within 5 kpc of the center for small ellipticals.

However, if more short GRBs are found at such intragalactic locations, a number of new possibilities may be favored: BH-NS mergers with small or zero BH kicks, or in general small kicks for both NS and BH (e.g., Podsiadlowski et al. 2004; Dewi et al. 2005). Such alternative models would then have to be investigated. We note that, at present, the necessity of imparting such small kicks to the majority of NS is an open question (c.f., Willems et al. 2004; Chaurasia & Bailes 2005; Ihm et al. 2005). This, combined with our results for the locations of the mergers, indicates that short GRBs in the outskirts of galaxies need not be associated with globular clusters, as recently claimed by Grindlay et al. (2006).

We find that short GRB progenitors originate most probably from a diverse population of compact objects which are formed in old but also in young stellar environments. Although the absolute formation rates and redshift distributions implied by a mixture of galaxy types must be investigated and compared with theoretical predictions in more detail (O'Shaughnessy et al., in preparation), at present we are able to account for the origin (and associated delay times) of several recently observed short GRBs.

Some of the recent work (e.g., Nakar, Gal-Yam & Fox 2005) stands in apparent contradiction with our findings, presenting claims that the current models of double compact objects cannot explain the new short GRB observations. Also, long delay times (~ 6 Gyr) are inferred from the associations of short GRBs with old elliptical galaxies (Nakar et al. 2005). We note that at present these should be considered with caution. First, they are based on the analysis of a very small number of bursts and may suffer from small number statistics; a significant fraction of short delay bursts cannot be ruled out with high statistical significance. The comparison in Nakar et al. (2005) has been performed using some trial functions of delays, which do not necessarily correspond to the actual delays obtained in detailed population synthesis calculations. Second, their analysis neglects the information about the types of individual short GRB host galaxies and their particular star formation histories. Third, the models of Nakar et al. (2005) cannot explain the observed Galactic population of relativistic double neutron stars, with merger times of

$\sim 100 - 3000$ Myr, that are consistent with our models (see Fig. 1). Finally, the estimate of the delays may be complicated by evolutionary effects. We do know that the population of long GRBs is affected by cosmological evolutionary effects, for example, related with the metallicity evolution of the Universe, and so may be the population of short GRBs. Thus a direct comparison with the total star formation rate as performed by Nakar et al. (2005) may be misleading. The influence of such evolutionary effects and of the contribution of different types of galaxies and their star formation history will be examined in detail in O'Shaughnessy et al. (2006).

Additionally, the findings of Nakar et al. (2005) should be weighted by the observations of GRB 050724 and GRB 051221A in young star forming environment, as well as the detection of GRB 050813 at z=1.7-1.9 where there ought be no short GRBs, if the delays are as long as they claim. If more short GRBs are found at high redshifts ($z \gtrsim 1$), this will provide further support for delay times, that at least for some short GRBs, are shorter than ~ 6 Gyr. It has also been suggested that there is an observational bias against detecting short GRBs at high redshifts with *SWIFT*; the minimum flux for detection is apparently smaller in the observed sample than for GRBs with

secure redshift determination, and therefore it favors redshift determinations for closest (low redshift) bursts (Hopman et al. 2006). If this is the case, then it is clear that the observed redshift distribution leads to an overestimate in delay times in the analysis of Nakar et al. (2005).

We conclude that the current observations point toward a short-hard GRB progenitor population that is diverse in terms of merger times and locations, as suggested by our models. Soon, with more observations of short GRBs, we will be able to critically test the population synthesis models. Specifically, we will investigate effects of low metallicity, binary populations dominated by roughly equal-mass binaries as suggested by Pinsonneault & Stanek (2006) and low natal kicks proposed by Pfahl et al. (2002) on progenitors of double neutron star systems, and their relevance for both short GRB and gravitational-wave observations (Belczynski et al. 2006, in preparation).

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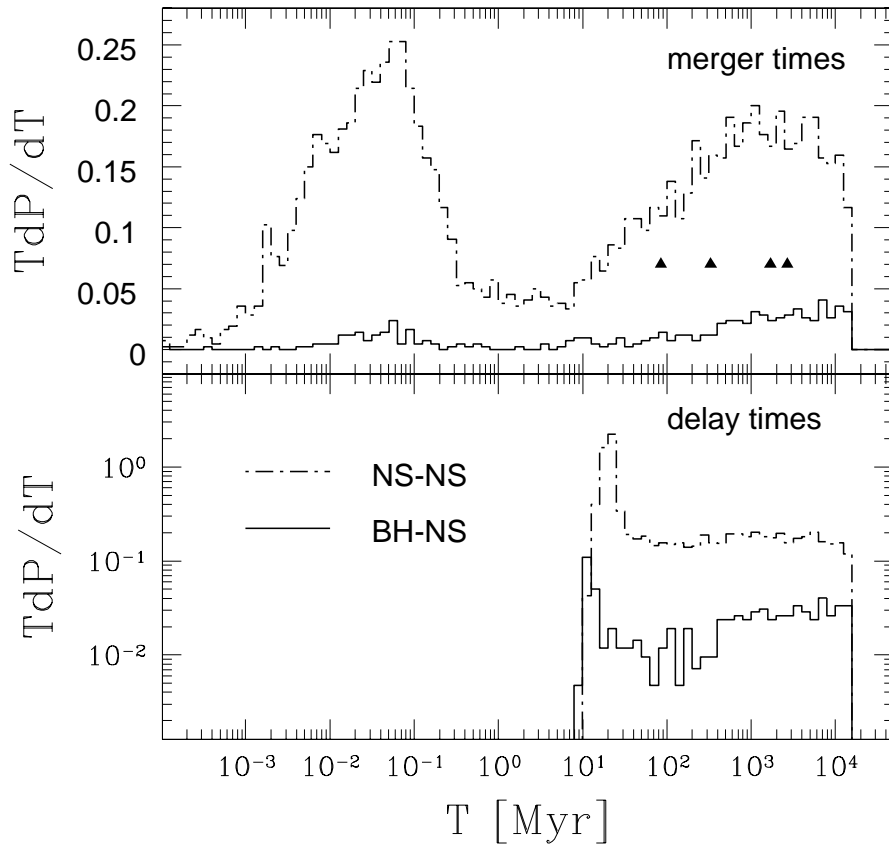Willems, B., Kalogera, V., & Henninger, M. 2004, ApJ, 616, 414

Fig. 1.— Top: merger time distributions for NS-NS and BH-NS coalescing binaries. The four field Galactic NS-NS systems are shown with triangles. Bottom: delay time distributions. Delay time includes both formation time of a double compact object binary (~ 20 Myr) as well as its merger time. Note the different vertical scales on the panels.
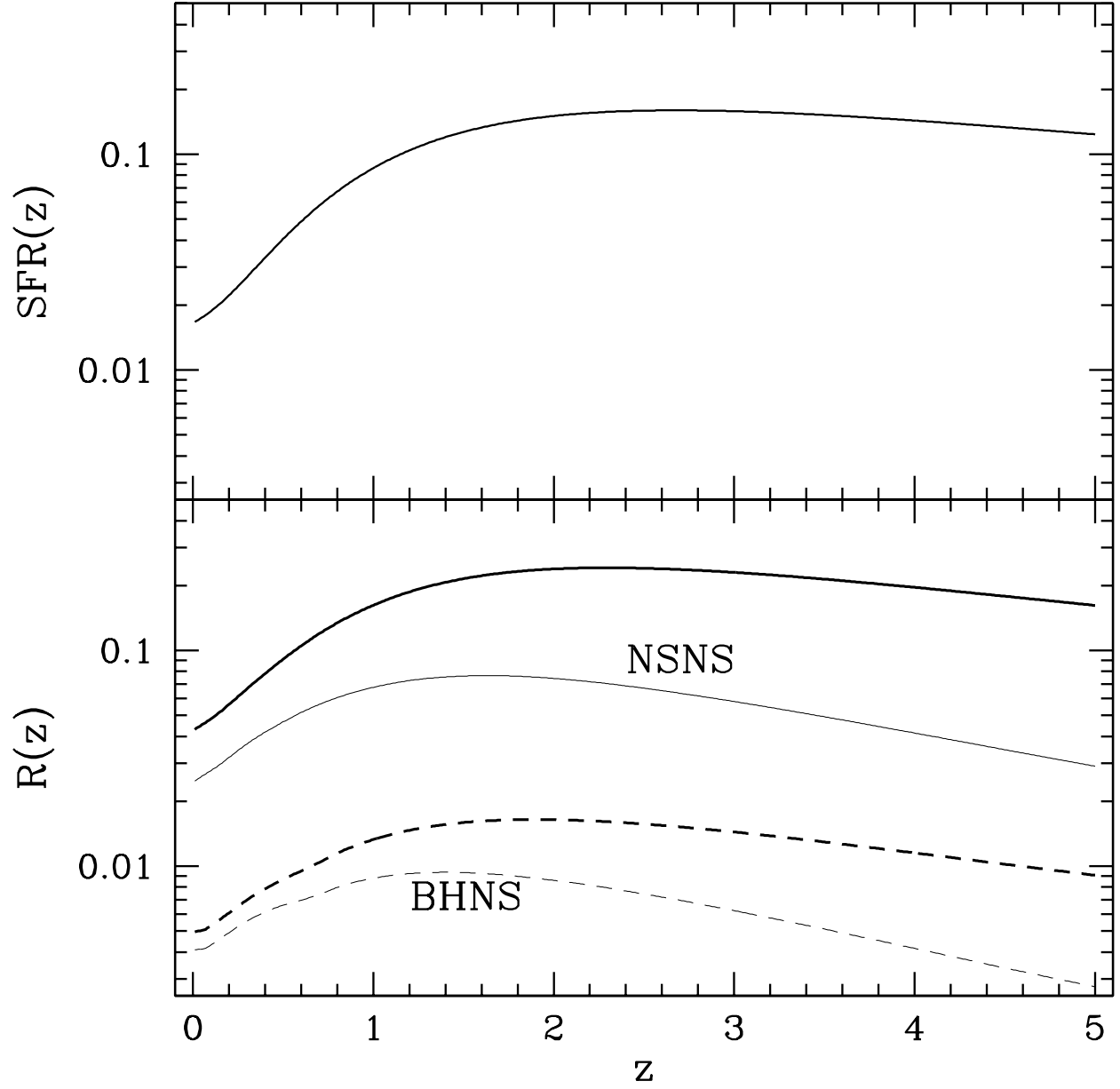
Fig. 2.— The top panel shows the star formation rate history we have used. The bottom panel (thick lines) shows the inferred merger rate as a function of redshift for the NS-NS and BH-NS mergers using the delay times distribution of Figure 1. The thin lines show the contribution from the long-lived ($t > 100$ Myr) population. Rates are in arbitrary units.
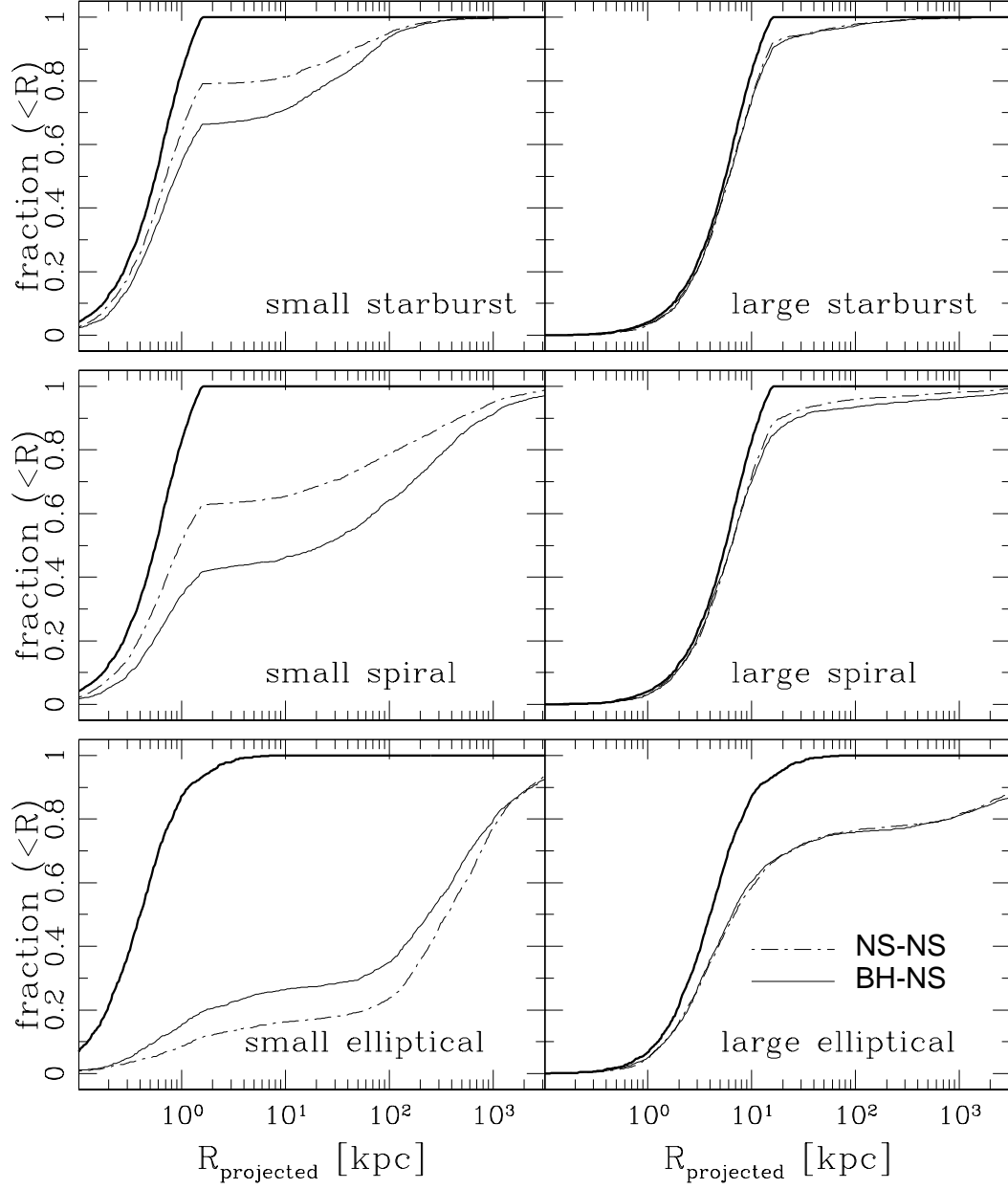
Fig. 3.— Cumulative distributions of double compact objects merger locations for different types of host galaxies. Initial distributions of binaries within each galaxy are shown with thick solid lines.
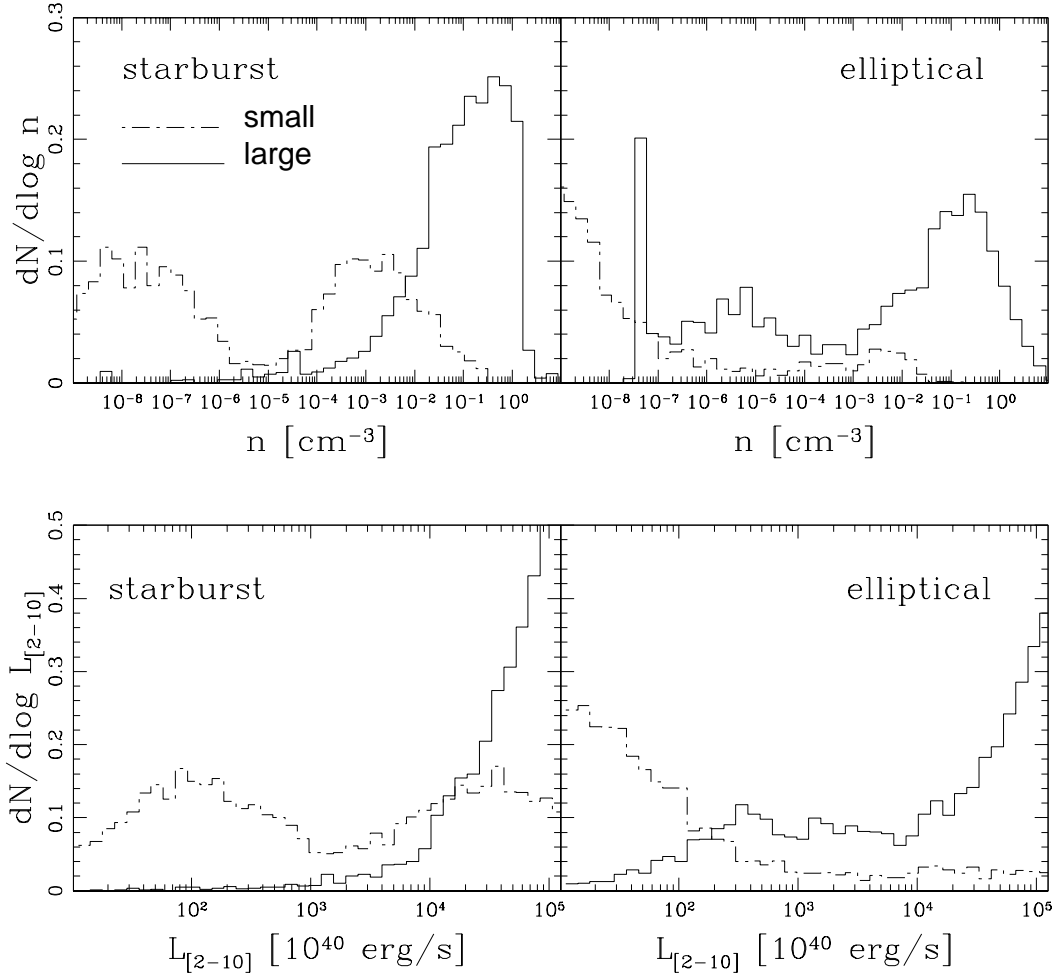
Fig. 4.— Probability distribution for density (top) and luminosity in the [2-10] keV band (bottom) for different environments in which the mergers take place.